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PROPOSED DYNAMIC PHASE DIFFERENCE METHOD FOR  
THE DETECTION OF TILE DEBONDING FROM THE SPACE  
SHUTTLE ORBITER

FOR REFERENCE

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PROPOSED DYNAMIC PHASE DIFFERENCE METHOD FOR THE DETECTION  
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By Allan J. Zuckerwar and Danny R. Sprinkle

INTRODUCTION

The space Shuttle orbiter thermal protection system consists of ceramic tiles bonded to thin nylon felt pads, known as strain isolator pads (SIP), which are composed of thousands of intertwined nylon filaments. The pads, in turn, are bonded to the aluminum skin (substrate) of the Shuttle orbiter (ref. 1). In service a tile or SIP may suffer severe deterioration due to mechanical loading, especially during the launch or reentry stages of a mission. It is desirable, upon completion of a mission, to test the continued serviceability of all 30 000 tile-SIP assemblies on the orbiter, a process called "recertification." The purpose of this paper is to describe a dynamic recertification procedure, based on the phase difference between the tile surface and the substrate, for detecting the loose tiles. The effort described here concentrates not on the tile proper, rather on the SIP and its bonding, for it is anticipated that therein will lie the primary sources of failure.

Several discussions with researchers familiar with the Shuttle thermal protection system have suggested the following general guidelines for developing candidate recertification techniques:

1. A global, noncontacting method is preferred in order to minimize turnaround time and tile breakage.

2. A static test to measure the tile rest position relative to the substrate or its neighbors may not be adequate, because the rest position may not be a reliable indicator of the physical condition of the tile.

3. A dynamic test, however, is subject to intractable difficulty as the result of the following unfavorable mechanical properties of the tile-SIP system:

a. Viscoplasticity. The force-displacement relationship is time-dependent, and the time dependence is a function of the displacement amplitude.

b. Hysteresis. The force-displacement relationship is multivalued, and because of irreversible changes in the SIP, depends upon the mechanical history of the system.

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c. Nonlinearity. The SIP is compliant up to a certain displacement level, beyond which it suddenly stiffens.

d. High damping. The quality factor  $Q$  is less than 2.

e. Anisotropy. The tile response is highly suppressed under normal excitation in comparison to lateral excitation, and even the latter depends upon the direction of excitation.

As a consequence of these properties, especially (d) and (e), it is concluded that the tile is most practically excited into lateral motion through the substrate. As is customary in measurement of lossy materials, the appropriate measure of the physical condition of the tile-SIP system is the phase relationship between the tile and substrate. Furthermore, such traditional linear concepts as "resonant frequency," "damping ratio," and "phase lag" will be used here in an approximate sense, even though they strictly apply only to a linear system.

Thus the development of the method consisted of two tasks: First, to find how the phase relationship depends upon the fatigue history of the SIP; secondly, to display this relationship in terms of a convenient visual display, amenable to rapid scanning of the tiles, so that recertification may be accomplished within an acceptable period of time.

#### PRINCIPLE OF MEASUREMENT

The test specimen, shown in figure 1, consists of a single tile and SIP assembly mounted on an aluminum plate. The plate is excited into lateral motion at constant amplitude and constant frequency between 30 and 240 Hz, a range which spans the resonant frequency of the tile-SIP system. The displacements  $x_1$  and  $x_2$  are measured by noncontacting sensors.

Linear theory yields the following relationship between  $x_1$  and  $x_2$ :

$$x_1 = \frac{f_o^2 x_2}{f_o^2 - f^2 + 2i f f_o \gamma} \quad (1)$$

where  $f_o$  is the resonant frequency of the tile-SIP system,  $\gamma$  the damping ratio ( $\gamma = 1$  for critical damping), and  $f$  the excitation frequency. From equation (1) is found the phase angle  $\phi$ :

$$\phi = -\tan^{-1} \left[ \frac{2ff_o\gamma}{(f_o^2 - f^2)} \right] \quad (2)$$

If the test specimen is illuminated by a stroboscope operating at a frequency slightly different from the excitation frequency, the relative motion between the tile and plate is readily discernible. The resulting visual effect, along with a plot of equation (2), is summarized in figure 2. At phase angles up to about 25°, where the motion is predominantly in-phase, the tile and plate are observed to move together. The displacements are large and easy to observe. Starting at about 25°, the out-of-phase component of the motion becomes discernible in the form of a beat between the two displacements, reaches a maximum at 90°, and falls off due to decreasing amplitude as the phase angle increases further. Above 120° the out-of-phase motion becomes ever more predominant, but the small amplitudes preclude observable motion without high magnification. The principle of the method proposed here exploits the dependence of the phase relationship of figure 2, and its associated visual effect, upon the fatigue history of the tile-SIP system.

#### EXPERIMENTAL PROCEDURE

The test setup, shown in figure 3, consisted of an excitation system, a tile assembly, and a detection system. The excitation system was made up of a function generator, which provided a sine-wave signal to a power amplifier, which in turn powered an 80 lb. vibration exciter. The tile assembly, composed of a 0.22 kg (0.48 lb.), 0.152 x 0.152 x 0.0476 m (6" x 6" x 1 7/8") densified tile bonded to a 6.58 kg (14.5 lb.) 0.305 x 0.305 x 0.0254 m (12" x 12" x 1") aluminum plate was suspended from a tripod by a single length of braided nylon lacing cord. The aluminum plate was coupled to the vibration exciter by a rigid connecting rod. Reference markers were attached to the tile and plate for the purpose of recording the observed motion on a video tape. The plate reference marker contained the tile identification number, fatigue history, excitation frequency, and excitation level. The tile marker identified the vertical or horizontal orientation. In practice, since the edge of the tile is an excellent object of observation, a tile marker will be unnecessary. The detection system consisted of two parts: (1) Proximity probes and (2) a video monitoring system. Two noncontacting sensors, a low-pass filter and an oscilloscope made up the first part. An eddy-current probe, positioned at the edge of the aluminum plate, and a photonic sensor, positioned at the edge of the tile, were used to provide analog voltage of the tile and plate displacements. The outputs from the sensors were displayed on the oscilloscope. A low-pass filter with a cutoff frequency of 30 KHz was used to filter out the carrier frequency of the eddy-current probe. A TV camera, video tape recorder, TV monitor, and stroboscope made up the video monitoring system.

The procedure called for mounting the tile assembly, testing, dismounting for proof-testing or fatigue cycling, and remounting. The testing proceeded by vibrating the tile assembly at 31, 61, 91, 121, 151, 181, 211, and 241 Hz at an acceleration level of 2 g rms, as controlled by the current into the vibration exciter. The stroboscope was adjusted to give an apparent tile motion of around 1 Hz. The above frequencies were chosen so that the difference frequencies would be multiples of 30 Hz to synchronize with the TV sweep. A 30-second recording was made showing the tile and plate in motion.

Output waveforms from the sensors as viewed on the oscilloscope were measured to obtain peak-to-peak voltages, calibrated to yield tile and plate displacements, and tile/plate phase differences, and these data were recorded. These steps were repeated for each excitation frequency, for each orientation of the tile assembly, and for each stage of tile fatigue. The only problem encountered in performing the tests was a somewhat difficult measurement of phase at the higher frequencies because of the reduced sensor outputs (especially photonic sensor) but this was not a major problem.

## RESULTS

Figure 4 shows the phase lag as a function of excitation frequency, at various stages of fatigue history of the test specimen, for two different plate orientations, one rotated 90° with respect to the other. A "virgin" tile was tested immediately after fabrication. A "proofed" tile was subjected to a static normal load of 10 psi. A fatigued tile was subjected to an alternating normal load of +10 psi for the number of cycles indicated. The frequency corresponding to a phase lag of 90° is defined as the "resonant frequency"  $f_o$ . The symbols are experimental points, and the solid lines are the least-squares fit to equation (2), using  $\gamma$  as the only adjustable parameter. The difference between theory and experiment is attributable in part to error in the phase angle measurement, but more so to the attempt to fit a linear theory to a nonlinear phenomenon, for the phase angle is dependent upon the excitation amplitude.

The trend of the data is governed by the occurrence of two physical phenomena. First, a shift of the phase response curves to the left with increasing fatigue loading is readily apparent, indicating a lowering of the resonant frequency. Secondly, the curves tend to flatten, i.e., to show a dwindling slope at the 90° phase point, with increasing fatigue. The corresponding increase in damping ratio  $\gamma$  manifests a general deterioration of the mechanical properties of the SIP material. In fact, for the  $\uparrow$  orientation the system even becomes overdamped at 4000 fatigue cycles. These trends are shown in figures 5 and 6. The data point out a marked influence of tile orientation with respect to the exciting force: The resonant frequencies differ by about 30 Hz for the two orientations. However, after 1000 fatigue cycles a significant out-of-phase component is observed at 61 Hz for both orientations.

Tests on a 5-inch thick tile in a highly fatigued state revealed out-of-phase motion at a frequency as low as 31 Hz.

The above tests suggest that a loose tile can be defined on the basis of the frequency at which out-of-phase motion becomes observable. This frequency, of course, will depend upon the thickness of the tile.

A "beat" between the motions of a reference marker and an edge of the tile, corresponding to out-of-phase motion, was found to be readily observable on a split-screen TV monitor. This is an important consideration, for a distinctive visual effect will serve as a key element in the global approach. The visual effect could possibly be enhanced by observation of Moire fringes.

## PRACTICAL APPLICATION TO THE SPACE SHUTTLE ORBITER

### Procedure

Recertification of the tiles on the space Shuttle orbiter by this method would comprise two basic steps: First, to excite the orbiter into fuselage axial motion between 30 and 60 Hz at a level of 2g; secondly, to scan the tiles with a TV monitor, under stroboscopic illumination at a small (e.g., 1 Hz) difference frequency, and to look for the out-of-phase motion characteristic of loose tiles. Suppose, for the sake of argument, that a tile is considered bad after sustaining the equivalent of 4000 fatigue cycles. Then according to figure 7 the orbiter would have to be excited at a frequency no lower than 45 Hz in order that out-of-phase motion be observed for both orientations.

The excitation system could be modeled after that used in the Orbiter 101 Horizontal Ground Vibration Test (HGVT) at the Rockwell Palmdale facility in July 1976 (ref. 2). The appropriate suspension would be the "rigid configuration" with the ET struts hard-mounted at the struts/ET interface. Several modifications would be required to increase the "x-translation" modal frequency from 0.338 Hz to the 30-60 Hz range: elimination of the air bags, redesign of a stiffer double rocker system, and rigid-body quality factor. The original exciter locations for this type of motion, designated as " $\phi 22RX$ " and " $\phi 23LX$ "--OMS right and left pod simulators--may prove inadequate. The proposed application dictates the selection of new locations and certainly an increase in the exciting force.

The detection system would require one or more reference markers rigidly attached to the aluminum skin of each of the four main substructures: forward fuselage-crew cabin, mid-fuselage-wing, aft fuselage, and vertical tail. The relative motion between reference marker and tile could be observed on a split-screen TV monitor in either real time or on a video tape recording. The observation time per tile should amount to no more than a few seconds.

Modal interference is not expected to be a disruptive problem. The HGVT was limited to frequencies below 30 Hz, the region containing the major structural modes. The closest free mode resembling the "x-translation" is "fuselage axial motion with vertical tail pitching" (rigid symmetric mode no. 7) at a frequency of 8.2 Hz, safely removed from the proposed recertification frequency region. Symmetric modes in the vicinity of 30 Hz include rolling, rotation, and bending of the elevons; torsion and bending of the wings; and bending of the vertical tail and body flap. Antisymmetric modes include second bending of the vertical tail and lower SSME and OMS out-of-phase axial motion. The absence of strong coupling of these modes to the excited rigid body axial mode should permit successful application of the proposed recertification procedure. In any case the specified excitation level of 2g lies well below design limits for static or fatigue damage to the structure.

### Anticipated Difficulties

Tile-SIP anisotropy.-According to figure 5 the orientational dependence of the lateral resonant frequency amounts to a difference of about 30 Hz in two normal directions, a figure taken to be typical for a tile-SIP system. The error due to this effect will result in the replacement of some good tiles. A possible countermeasure would be better control of the orientation in the application of the SIP material.

Filler bar.- The presence of filler bar between the tiles could conceivably impede lateral motion of the tile. Later experiments on a multi-tile panel, however, have shown the effect of the filler bar to be negligible.

Tile thickness.-Since the resonant frequency varies as the square root of the tile thickness, the criterion for failure should take the tile thickness into account. The frequency at which out-of-phase motion is first observed will thus be lower for a thicker tile. The tile area, on the other hand, will have no effect on the resonant frequency, for the SIP stiffness and tile mass are both proportional to area.

Curved tiles.-Curved tiles on the leading edge of the wing and nose of the fuselage will not be excited by axial motion and do not lend themselves to this technique.

Objection to exciting the orbiter continuously at a single frequency.-A possible alternative to single-frequency excitation would be excitation at a random frequency between 30 and 60 Hz (at constant amplitude). Relative motion between the tile and reference marker could conceivably be observed through computer-controlled triggering of the stroboscope lamp.

### CONCLUSIONS

The correspondence between out-of-phase lateral motion and stage of fatigue of the tile-SIP assembly has been clearly demonstrated. That this relationship can be monitored visually under stroboscopic illumination makes it a viable approach to semi-global recertification. Sources of error include SIP anisotropy, varying tile thickness, and the impeding effect of filler bar. Anisotropy is the most serious of these but can possibly be countered through improved control of the SIP manufacture and processing. In a practical application of this method to the orbiter, the excitation and suspension systems could be modeled after those cited in the Rockwell test.

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2. Bejmuk, B.: Space Shuttle Vehicle and System Dynamics Data Book, Vol. IA, Orbiter-101 Horizontal Ground Vibration Test Data Book. Rockwell Report SD 75-SH-0032, Vol. IA, December 1976.

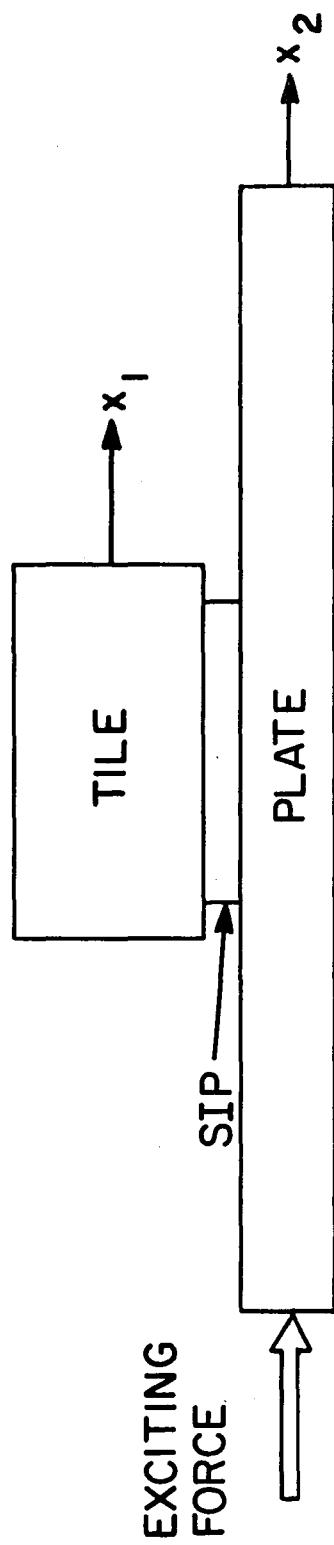


Figure 1. Configuration of the Tile, SIP, and Aluminum Plate.

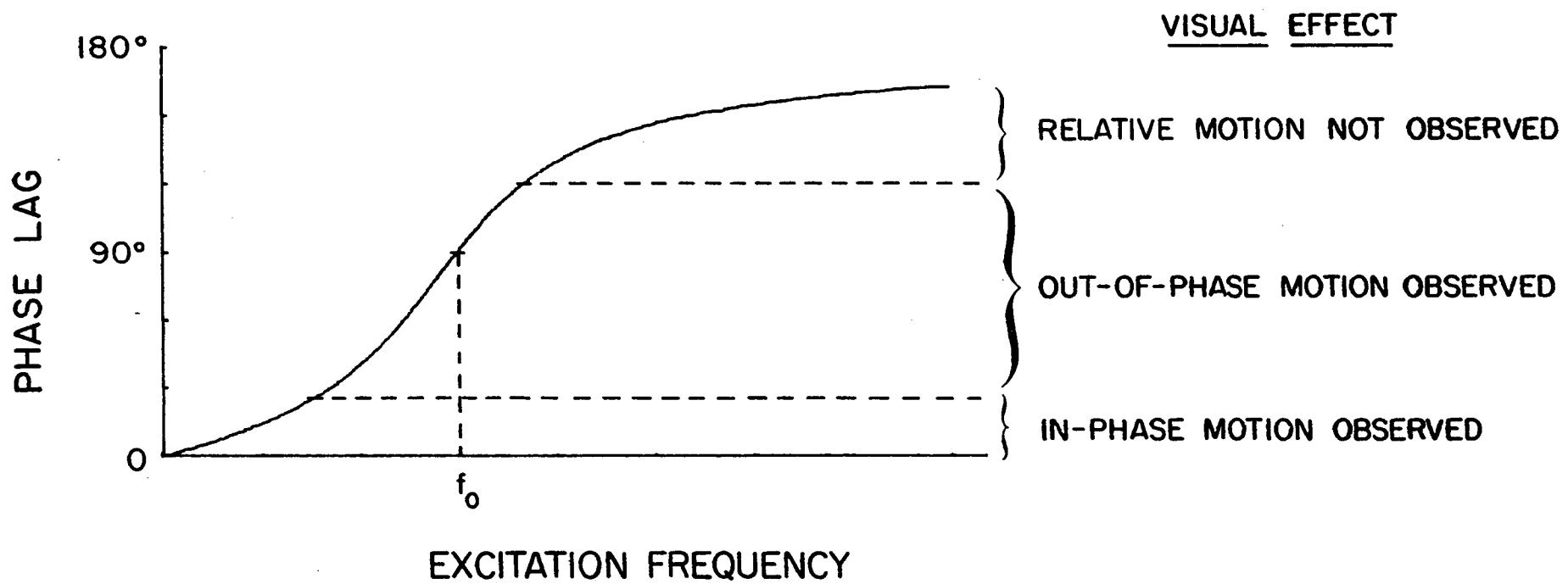


Figure 2. Phase Lag Between Tile and Substrate, and Associated Visual Effect Under Stroboscopic Illumination.

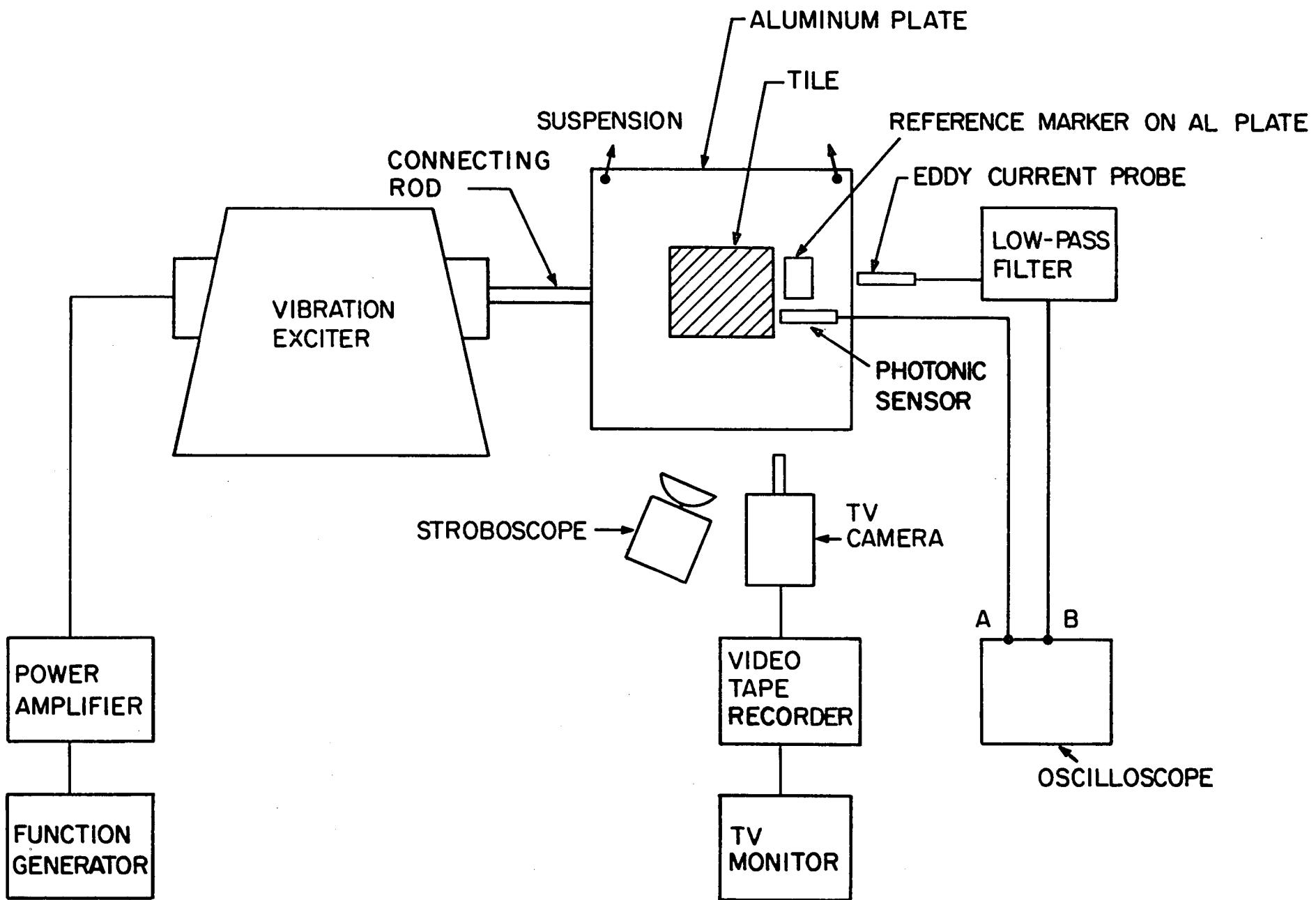


Figure 3. Setup of Laboratory Test.

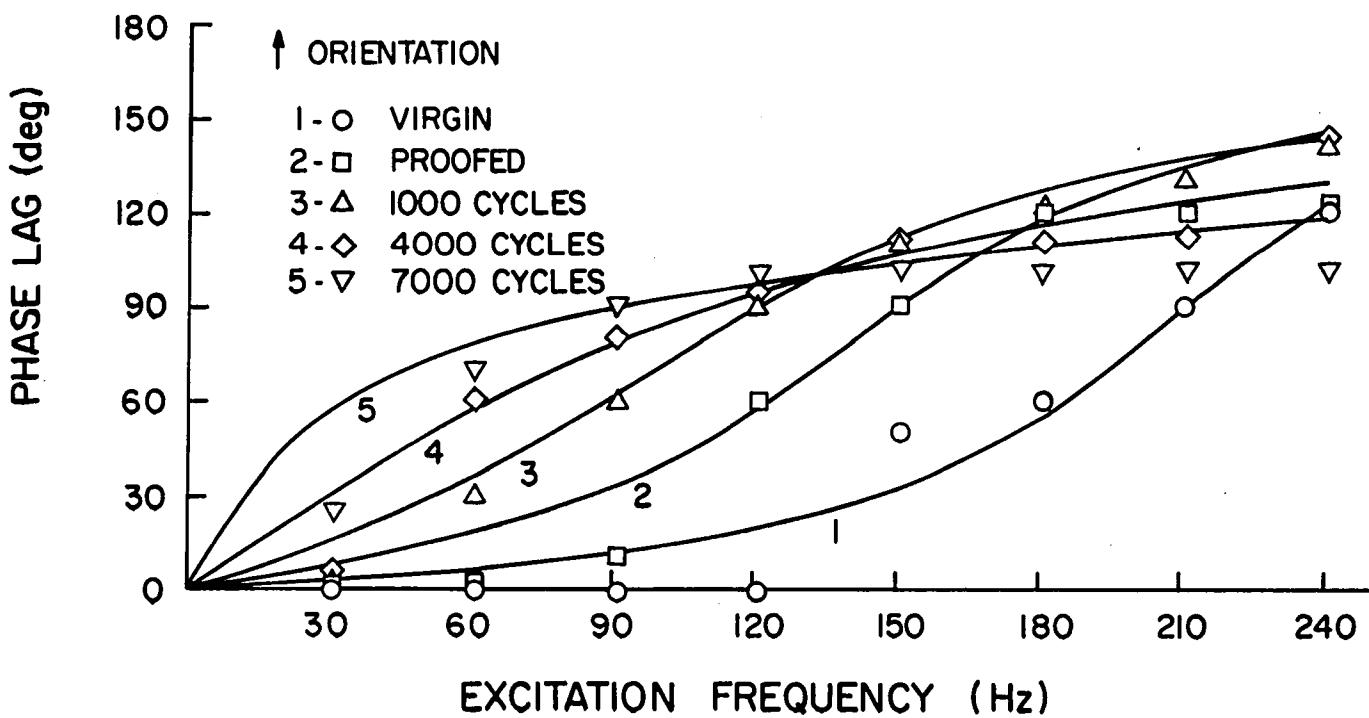
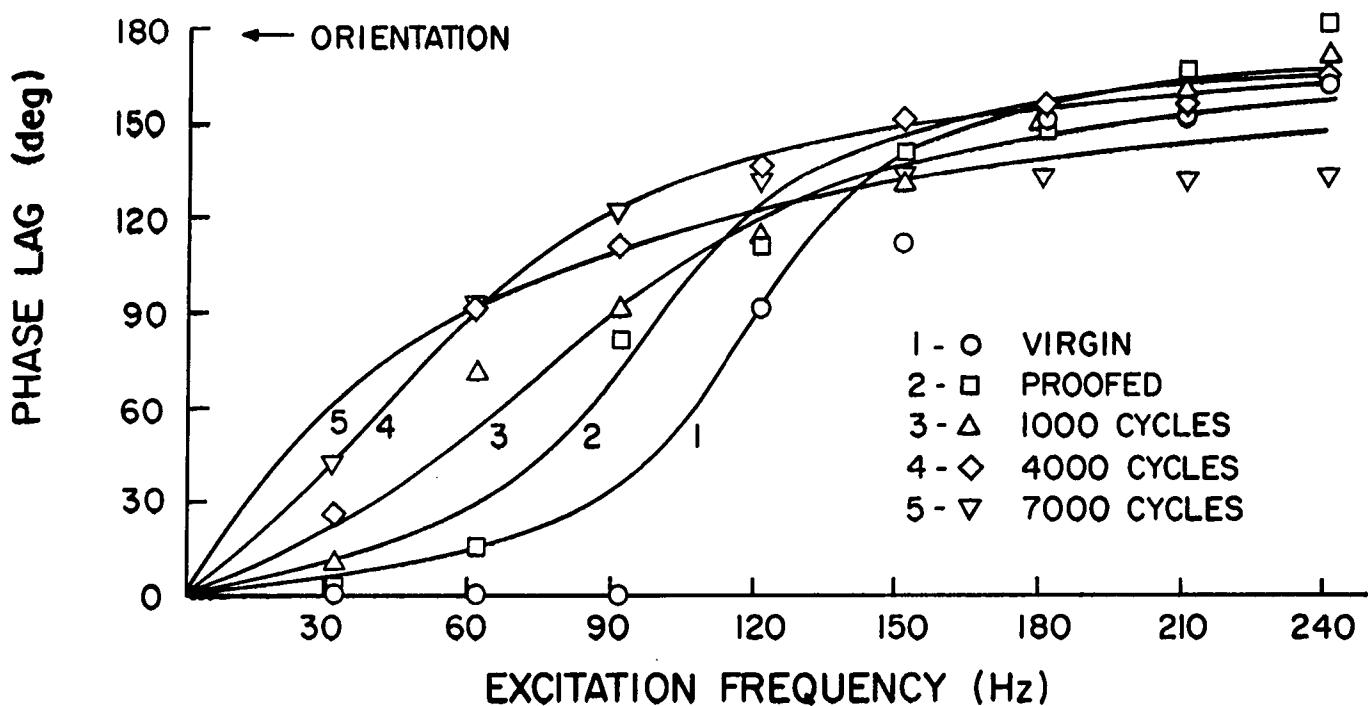


Figure 4. Phase Lag Versus Excitation Frequency at Various Stages of Fatigue Loading for Two Different Tile Orientations. The Excitation Level is 2g. Solid Lines are Best Fit to Equation (2) and Symbols are Experimental Points.

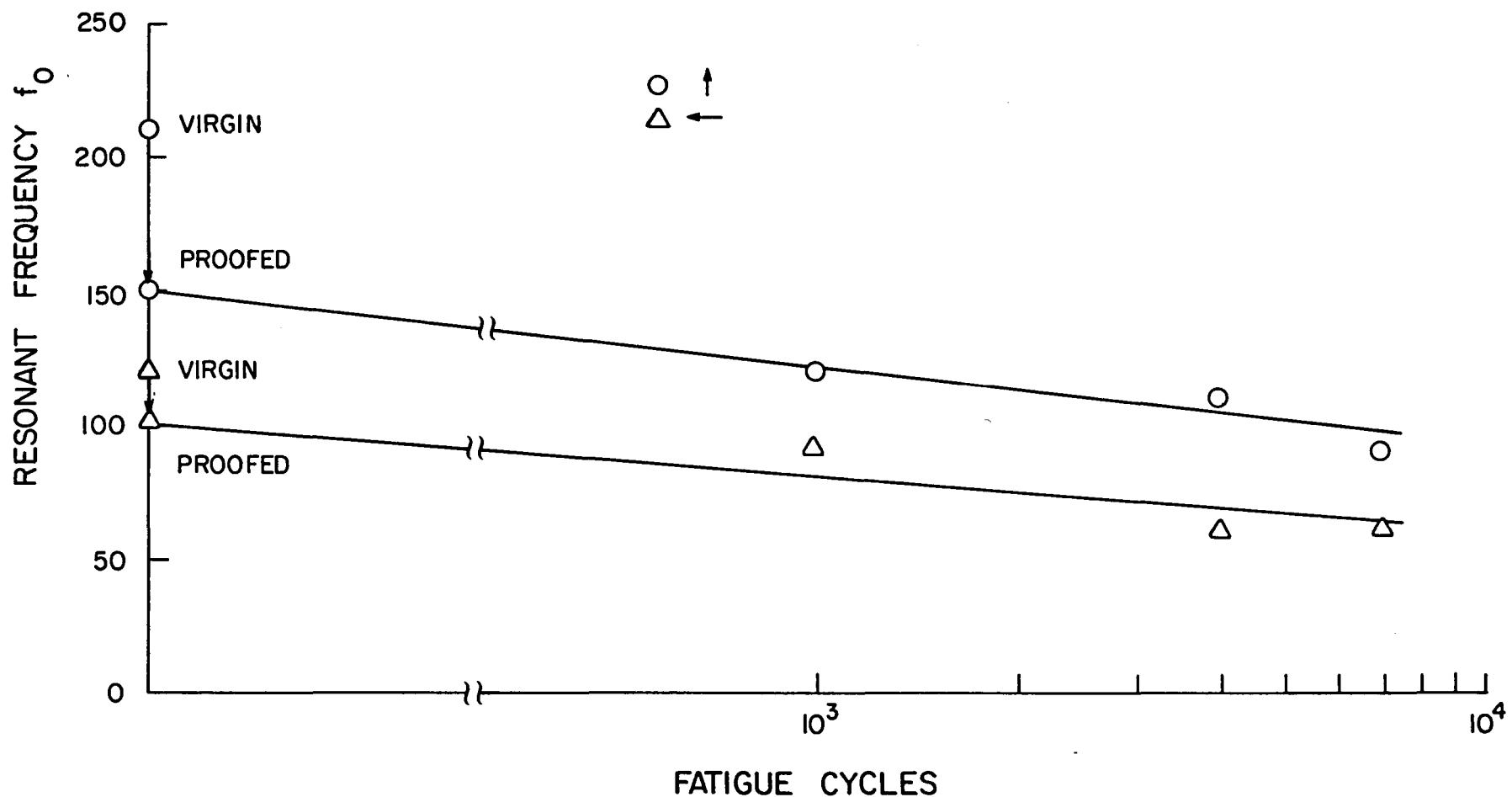


Figure 5. Resonant Frequency at Various Stages of Fatigue Loading for Two Different Tile Orientations.

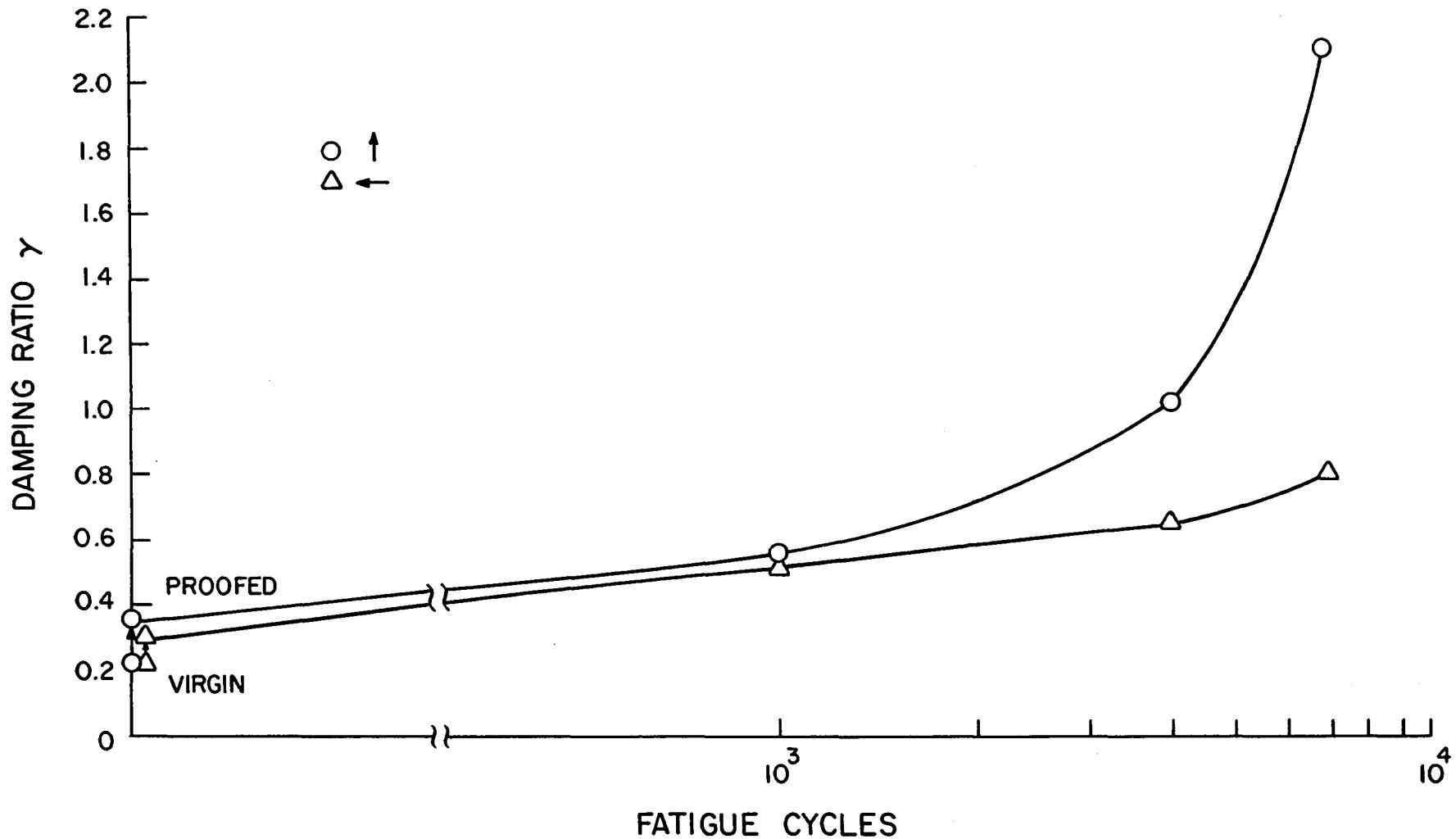


Figure 6. Damping Ratio at Various Stages of Fatigue Loading for Two Different Tile Orientations.

FREQUENCY AT WHICH OUT-OF-PHASE MOTION IS FIRST OBSERVED  
VS. FATIGUE CYCLES

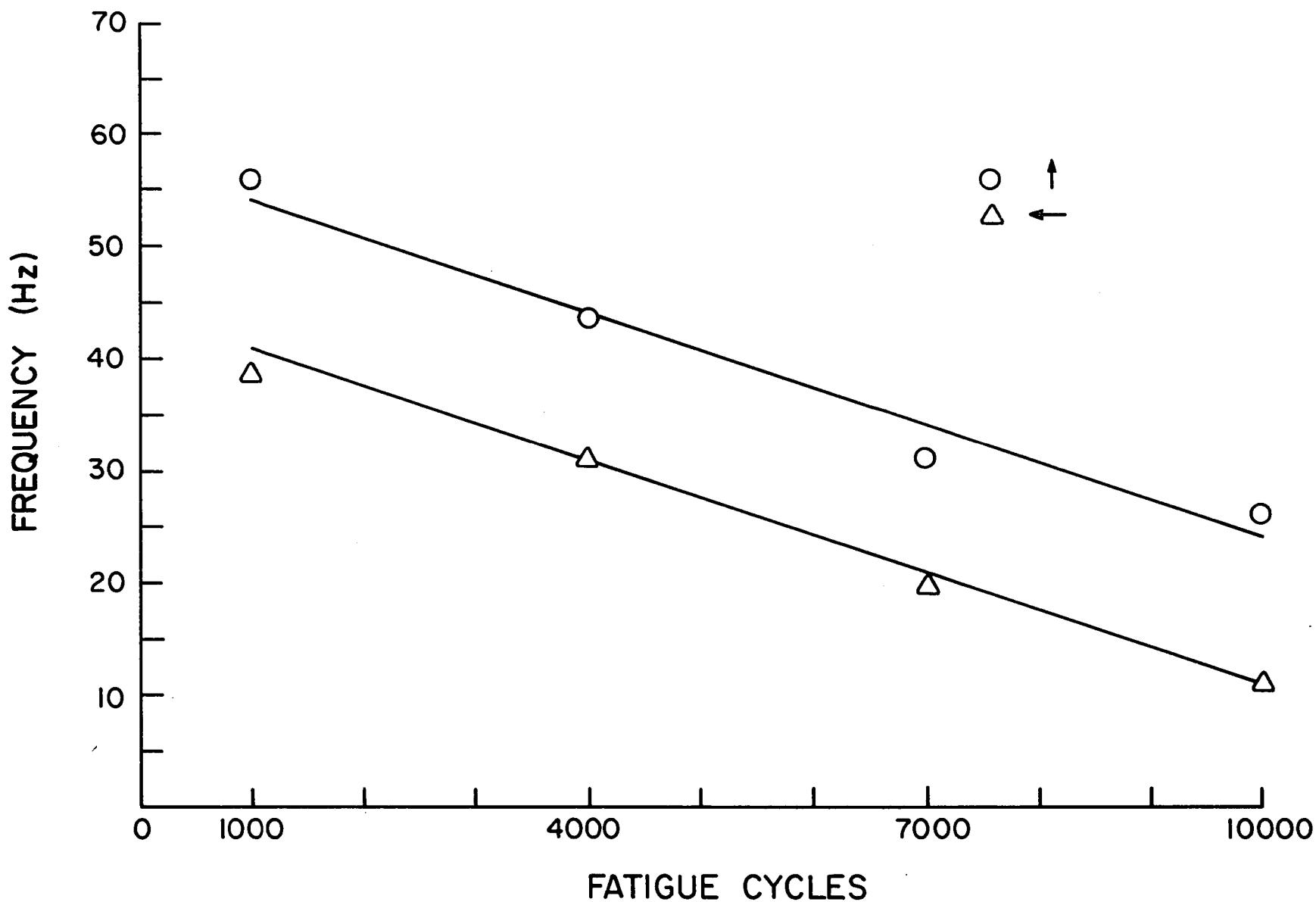


Figure 7. Frequency at Which Out-of-Phase Motion is First Observed Vs. Fatigue Cycles.

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16. Abstract  A noncontacting, semi-global, dynamic technique has been developed for detecting loose tiles on the space Shuttle orbiter. In laboratory tests on a single tile, the substrate was excited into lateral motion at a constant frequency and amplitude of 2g. The phase relationship between the motions of tile and substrate was examined by two methods: First, by noncontacting probes in order to relate the dynamic properties of the tile-SIP system to its fatigue history; secondly, by a visual technique using a stroboscope and split-screen video monitor for practical application in the field. When the substrate is excited at an appropriate frequency (between 30 and 60 Hz) a good tile moves in phase and a loose tile out of phase with the substrate. The out-of-phase motion is readily observable in the form of a "beat" between the tile and a reference marker on the substrate.			
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